Design and Validation of a Multi-Port Converter for Renewable Energy Applications

Alaa A. Mahmoud[1], **Mahmoud A. Ahmed**[1, *], **Ahmed A. Hafez**[2]

[1] Electrical Dept., Faculty of Technology and Education, Sohag University, Sohag, Egypt.
Alaa-Abd-El_samee@techedu.sohag.edu.eg; Mahmoud_Ahmed@techedu.sohag.edu.eg
[2] Elect. Eng. Dept., Faculty of Engineering, Assiut University, Assiut, Egypt; prof.hafez@aun.edu.eg

Abstract

This paper presents the design, simulation, and experimental validation for a non-isolated multi-port converter (MPC) tailored for renewable energy applications such as microgrids and electric vehicles. The proposed converter architecture supports multiple power sources specially, a photovoltaic (PV) panel and a lithium-ion battery pack within a unified power interface. MATLAB Simulink was used for system-level analysis, and a hardware prototype was developed to confirm simulation accuracy. The control strategy dynamically adapts to three distinct operating modes based on source availability and load demand, thereby ensuring continuous and optimized energy delivery. Experimental results closely matched simulations, demonstrating the effectiveness of the proposed topology in achieving stable voltage regulation, efficient power sharing, and seamless mode transitions.

Keywords: Multi-port Converter, Renewable energy sources, EV, Microgrid.

1. Introduction

Climate change and global warming are driving the move toward Renewable Energy Sources (RES) as a cleaner, more sustainable option than fossil fuels [1]. However, a key challenge with RES is their unpredictability—their power generation depends on environmental conditions like sunlight and wind speed. To manage these variations and ensure smooth integration with traditional power grids, advanced power converters are crucial [2]–[7]. These converters help stabilize power supply and allow easy switching between grid-connected and off-grid systems.

Solar PV systems generate clean electricity from sunlight and are used in renewable energy applications for instance microgrids and EVs [8] [9], [10]. They power connected loads and charge batteries when sunlight is available. However, their efficiency can drop due to varying sunlight intensity, and their power output is not always consistent. To maximize energy harvest, Maximum Power Point Tracking (MPPT) was used. Additionally, solar PV systems are often combined with battery storage, creating a hybrid system that ensures a stable power supply. This setup is particularly useful for handling high-power demands, such as in electric vehicles during high-speed driving or on rough terrain [11]–[14].

Using separate converters for every source leads to a larger system, complex, and expensive. Instead, a single converter that can handle different voltage inputs is needed to manage multiple energy sources efficiently. Hybrid energy storage systems usually connect to a multi-port converter. These converters come in different types, depending on whether they need isolation or non-isolation between inputs and outputs.

Multi-port converters (MPCs) are sophisticated power electronic systems that integrate multiple energy sources and loads into a single compact unit, offering significant advantages for applications like electric vehicles, renewable energy systems, and microgrids. By consolidating multiple power conversion stages into one device, MPCs reduce component count, simplify system architecture, and improve both power density and overall efficiency in comparison to traditional converter setups. These converters are primarily categorized into isolated and non-isolated types [15], with isolated MPCs providing enhanced safety through electrical separation between ports, while non-isolated versions deliver higher efficiency and cost-effectiveness. Ongoing research focuses on optimizing MPC performance through improved voltage gain capabilities and enhanced energy storage integration techniques [16], making them increasingly vital for modern power management solutions.

Multi-port converters (MPCs) represent a specialized class of power converters [17], [18] capable of featuring multiple input and/or output terminals, their ability to integrate different energy sources ensures continuous, reliable power delivery to connected loads [11]–[13], [19]. By consolidating multiple power conversion stages into a single unit, MPCs achieve higher system efficiency while maintaining a more compact physical footprint compared to conventional solutions [20]. A key advantage lies in their reduced component count relative to systems using separate converters. These characteristics have made MPCs particularly valuable for mobile applications, with electric vehicles representing one prominent implementation area [21].

In [22], an MPC integrates supercapacitors and batteries using a dual-active bridge topology, providing isolated bidirectional power flow. Ref. [23] presents a simplified bidirectional MPC that achieves high voltage gain at low input voltages while maintaining efficient power transfer in both directions. Additionally, [24] introduces an interleaved MPC design that combines coupled-inductor and switched-capacitor circuits to enhance voltage gain and reduce voltage stress.

A converter design introduced in [25] With one battery and two solar cells for extra storage. For the input ports, the

Maximum Power Point Tracker is used; for the load port a Proportional Integrator (PI) controller was employed. Ref. [26] Presented a high gain converter employs two switches driven by one PWM signal. It provides three outputs and utilizes the switched-capacitor and switched inductor technique. The converter is suitable for switched-mode power supply and RES applications.

Presented in [27] an isolated MPC Integrates several EVs with homes in microgrids. The converter performs the functions of an inverter, a transformer, and two bidirectional converters. While monitoring the optimal energy flow between the homes and EVs by combining two EVs energy.

This paper claims to have these contributions:

- This study introduces a novel, compact, and scalable non-isolated multi-port converter that integrates PV panels and battery storage within a unified system.
- A dynamic control strategy is developed to manage energy flow efficiently across Battery Mode, PV and Battery Mode, and Charging Mode.
- The proposed system is validated through MATLAB Simulink simulations and hardware experiments, showing strong agreement between results.
- The converter supports modular expansion to accommodate additional sources like supercapacitors and fuel cells, enhancing its applicability in diverse renewable energy systems.
- High voltage stability with minimal ripple is achieved across all operating modes, ensuring clean and reliable power output.

The remainder of this paper is as follows; the multiport converter design is explained in Section 2. Operation modes are given in Section 3. Section 4 provides the results. Finally, Section 5 introduces the conclusions.

2. Multiport Converter design

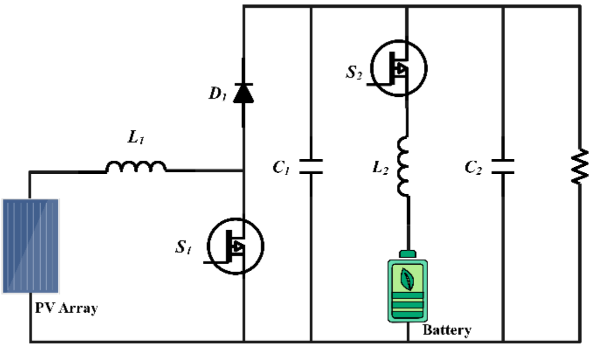

Fig. 1. Layout of the system under concern.

The MPC in this work is a non-isolated and modular converter as shown in Fig. 1.

The MPC consists of three ports as follows:

a solar PV panel with a voltage of 12 volts and power of 100 watts, a 7S10P lithium-ion battery pack with a voltage of 24volts and a capacity of 10 Ah, and an output port. More input ports could be connected to the MPC such as super capacitors, fuel cells etc., which provide continuous energy supply and interfacing different energy sources to different load types.

The performance of the proposed system was investigated in MATLAB Simulink. The simulation parameters for the system are given in Table 1, these parameters were calculated using the equations in [28], after simulations a prototype was built and tested with resistive load.

Table 1
The simulation parameters for the system.

Parameters	Value
L_1	$100\ \mu H$
C_1	$2200\ \mu F$
L_2	$700\ \mu H$
C_2	$100\ \mu F$

3. Operation Modes

The switches control the charging of the battery form the solar panel alongside the power flow between the load and the battery, as illustrated in Fig. 1. A flowchart for the MPC converter control strategy is shown on Fig. 2. The structure was analyzed in three distinct modes depending on the availability of solar power and the battery's state of charge.

A. Mode 1: Battery Mode

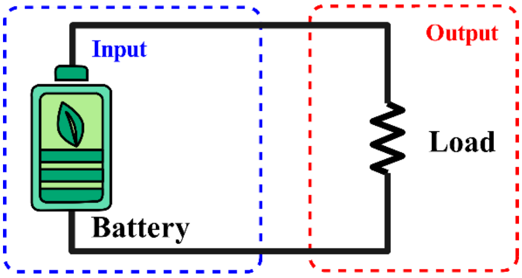

Fig. 2. Block daigram of Mode 1.

In this mode, the PV source is either inactive or not generating sufficient power shown in Fig. 2. The system relies entirely on the battery to supply the load. Operation in this mode is allowed only if the battery voltage remains above a minimum safe level ($V_{batt} > V_{min}$). This mode ensures power continuity during periods of low or no solar irradiance, such as at night or during cloudy weather conditions.

B. Mode 2: PV and Battery Mode

Mode 2 is activated when the available PV power is insufficient to meet the load demand ($PV < P_{out}$), but the PV source is still generating some power shown in Fig. 3. In this case, the system combines the PV output with battery, when the battery voltage is above the minimum threshold ($V_{batt} > V_{min}$). This mode allows for effective power sharing between the battery and PV, maintaining supply to the load without fully discharging battery.

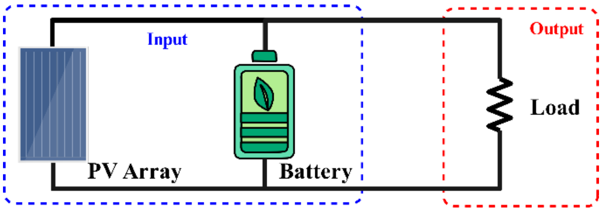

Fig. 3. Block daigram of Mode 2.

C. Mode 3: Charging Mode

When the PV power exceeds the load ($P_{PV} > P_{out}$) and the battery is not yet fully charged ($V_{batt} < V_{max}$), the system enters Mode 3 shown in Fig. 4. In this mode, the spare energy from the PV is directed to charge the battery. This mode ensures maximum utilization of renewable energy.

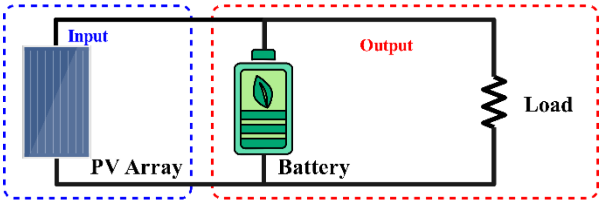

Fig. 4. Block daigram of Mode 3.

A flowchart of the converter control strategy is shown on Fig. 5, control process begins by checking whether the PV system is generating power ($P_{PV} > 0$). If no solar power is available, the system monitors the battery voltage, If $V_{batt} > V_{min}$, the system operates in Mode 1 (Battery Mode), where the load is powered by the battery alone. If solar power is available the PV output is compared with the load, When $P_{PV} > P_{out}$, the system determines whether the battery can be charged. If $V_{batt} < V_{max}$, it enters Mode 3 (Charging Mode), utilizing the solar PV energy to charge the battery.

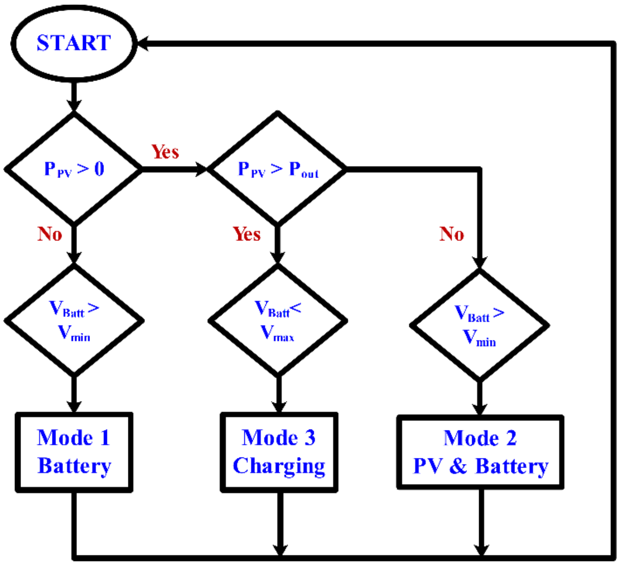

Fig. 5. Flowchart for the proposed converter control strategy.

In cases where $P_{PV} < P_{out}$, the controller again checks the battery voltage. If $V_{batt} > V_{min}$, the system operates in Mode 2 (PV and Battery Mode), supplying the load using a combination of PV power and battery energy. This control strategy ensures maximum utilization of renewable energy while maintaining the battery and providing continuous power to the load.

4. Results and Discussion

The MPC converter was designed and simulated in MATLAB Simulink software; Prototype was built to verify the simulations using IRF540 MOSFETs, a gate drive module based on TLP250 optocoupler, 18 ohms power resistor as a load and the PWM signals where generated using an Arduino UNO board. Fig. 6 shows the prototype while Table 2 lists the components

Table 2

Components used in the system prototype.

Component	Value
PV Panel	100 w 24v
Battery Capacity	10 Ah
MOSFET	IRF540
Gate Driver	TLP250
Load	18 ohms
Switching Frequency	10 kHz
Switching Board	Arduino UNO

Fig. 7. Ilustates the PWM signals for the MOSFETs and the output waveforms of each mode versus the experimental waveforms are illustrated in the following figures.

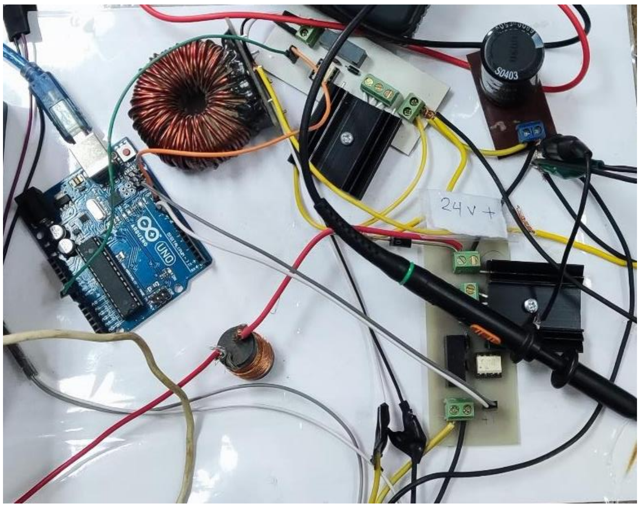

Fig. 6. The Expermental System.

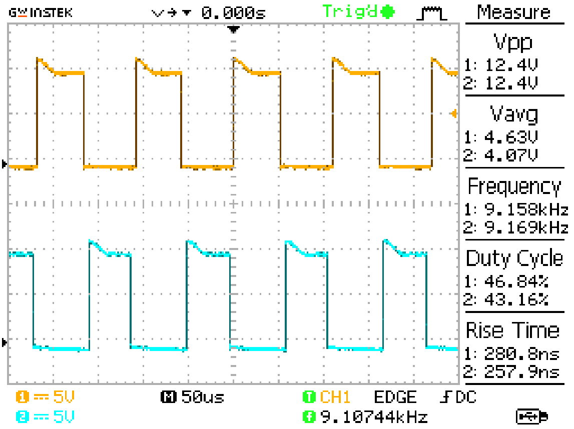

Fig. 7. Switches S1 and S2 PWM signals.

Mode 1

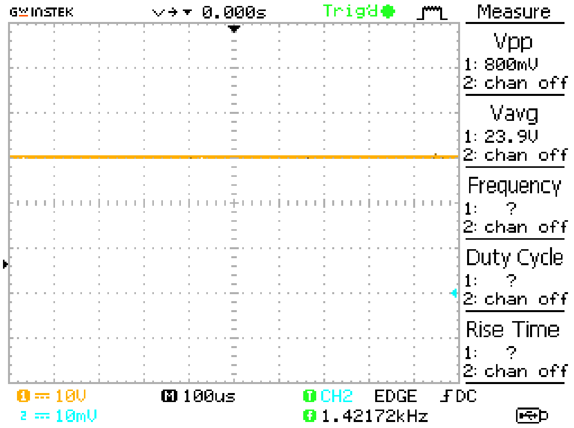

Fig. 8. Lithuim Battery to load (18 Ohms) Mersured

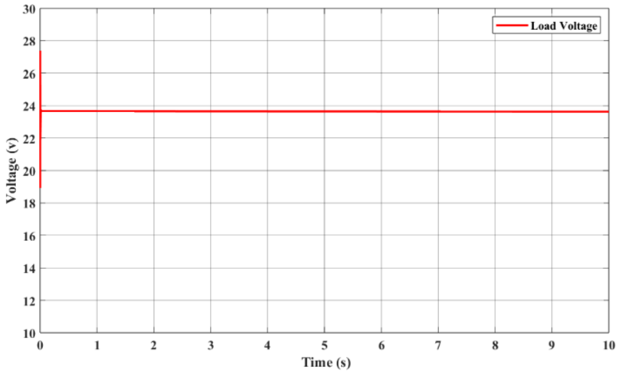

Fig. 9. Lithuim Battery to load (18 Ohms) Simulation

In this mode the testing was done with an 18 ohms resistive load, and the battery voltage was around 24 V. The simulation showed a stable output voltage with very little ripple, indicating smooth operation as shown in Fig. 9. The experimental prototype gave similar results. The output voltage remained steady, and the ripple was minimal as shown in Fig. 8. This shows that the battery and control system worked well to supply clean power to the load, and the simulation results matched the real-world performance closely.

Mode 2

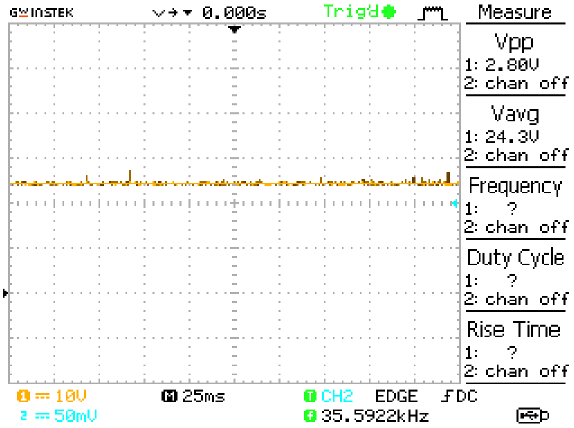

Fig. 10. PV and Battery to load (18 Ohms) Mersured

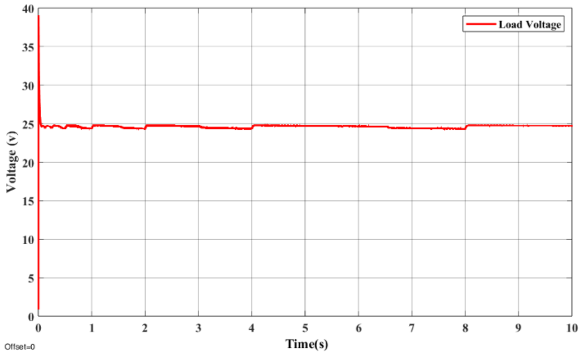

Fig. 11. PV and Battery to load (18 Ohms) Simulation

PV and the battery work together to provide power to the load. During testing, load voltage was about 24.5 V, which remained stable throughout the operation, The simulation results showed a smooth voltage waveform with very little ripple, indicating that the power sharing between the PV and battery was well-balanced shown in Fig. 11. The experimental prototype confirmed this behaviour, with a steady output voltage and minimal ripple shown in Fig. 10. This shows that the converter successfully combines power from both sources to maintain reliable output when solar power is limited.

Mode 3

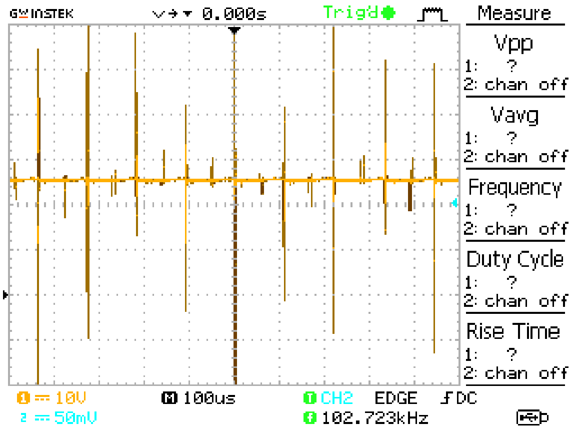

Fig. 12. PV Charging the Battery Mersured

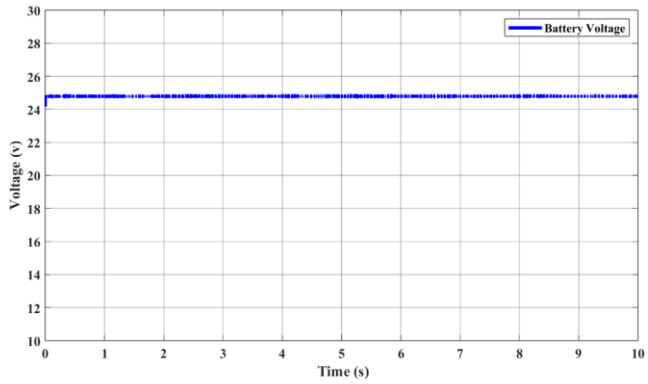

Fig. 13. PV Charging the Battery Simulation

During Mode 3, multi-port converter uses excess PV power to charge the battery and supplying power to load. During testing, the charging voltage was around 24 V with a charging current of approximately 2 A. The simulation showed a charging cycle with low ripple in both voltage and current, indicating stable operation as shown in Fig. 13. The experimental results closely matched the simulation, with steady charging and minimal fluctuations as in Fig .12. This confirms that the converter effectively manages energy flow and provides clean, controlled charging for the battery.

5. Conclusion

This work successfully presents a modular and efficient non-isolated multi-port converter capable of interfacing multiple renewable energy sources for distributed power applications. The converter's operation was validated through both simulation and experimental prototypes, revealing a high degree of consistency in voltage regulation, power sharing, and energy management across varying load conditions. The implemented control strategy ensures adaptive response to source availability, maximizing renewable energy utilization while maintaining uninterrupted load supply. This research provides a foundation for scalable and cost-effective energy conversion systems suitable for future smart grid and electric vehicle technologies. Future work may explore integration with other energy storage elements and implementation of more advanced control techniques such as artificial intelligence-based optimization.

References

[1] REN21, *Renewables 2020 Global Status Report http://www.ren21.net/resources/publications/*. 2020. [Online]. Available: http://www.ren21.net/resources/publications/

[2] J. G. Kassakian and T. M. Jahns, "Evolving and emerging applications of power electronics in systems," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 1, no. 2, pp. 47–58, 2013, doi: 10.1109/JESTPE.2013.2271111.

[3] Ó. Lucía, I. Cvetkovic, H. Sarnago, D. Boroyevich, P. Mattavelli, and F. C. Lee, "Design of home appliances for a DC-based nanogrid system: An induction range study case," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 1, no. 4, pp. 315–326, 2013, doi: 10.1109/JESTPE.2013.2283224.

[4] J. Carr, J. C. Balda, and A. Mantooth, "A high frequency link multiport converter utility interface for renewable energy resources with integrated energy storage," *2010 IEEE Energy Convers. Congr. Expo. ECCE 2010 - Proc.*, pp. 3541–3548, 2010, doi: 10.1109/ECCE.2010.5617702.

[5] W. Qiao, A. Sharma, J. L. Hudgins, E. G. Jones, and L. Rilett, "Wind/solar hybrid generation-based roadway microgrids," in *2011 IEEE Power and Energy Society General Meeting*, Jul. 2011, pp. 1–7. doi: 10.1109/PES.2011.6039884.

[6] Z. Qian, O. Abdel-Rahman, and I. Batarseh, "An integrated four-port DC/DC converter for renewable energy applications," *IEEE Trans. Power Electron.*, vol. 25, no. 7, pp. 1877–1887, 2010, doi: 10.1109/TPEL.2010.2043119.

[7] S. Y. Yu and A. Kwasinski, "Analysis of soft-switching isolated time-sharing multiple-input converters for DC distribution systems," *IEEE Trans. Power Electron.*, vol. 28, no. 4, pp. 1783–1794, 2013, doi: 10.1109/TPEL.2012.2211040.

[8] S. Reddi Khasim and C. Dhanamjayulu, "Selection parameters and synthesis of multi-input converters for electric vehicles: An overview," *Renew. Sustain. Energy Rev.*, vol. 141, p. 110804, May 2021, doi: 10.1016/j.rser.2021.110804.

[9] A. A. Hafez, A. A. Mahmoud, and A. M. Yousef, "Robust and Intelligent Control for Single-stage Grid-Connected Modular Multilevel Converter in PV Applications," *J. Electr. Eng. Technol.*, vol. 16, no. 2, pp. 917–931, Mar. 2021, doi: 10.1007/s42835-020-00639-8.

[10] A. A. Mahmoud, A. A. Hafez, A. M. Yousef, M. A. Gaafar, M. Orabi, and A. F. M. Ali, "Fault-tolerant modular multilevel converter for a seamless transition between stand-alone and grid-connected microgrid," *IET Power Electron.*, vol. 16, no. 1, pp. 11–25, Jan. 2023, doi: 10.1049/pel2.12359.

[11] N. Eskandarian, A. T. Harchegani, and S. S. Kazemi, "A novel structure for high step-up DC-DC converter with flexibility under the variable loads for EV solar charging system," *Int. Trans. Electr. Energy Syst.*, vol. 30, no. 6, Jun. 2020, doi: 10.1002/2050-7038.12375.

[12] M. Zandi, A. Payman, J.-P. Martin, S. Pierfederici, B. Davat, and F. Meibody-Tabar, "Energy Management of a Fuel Cell/Supercapacitor/Battery Power Source for Electric Vehicular Applications," *IEEE Trans. Veh. Technol.*, vol. 60, no. 2, pp. 433–443, Feb. 2011, doi: 10.1109/TVT.2010.2091433.

[13] C. -C. Lin, L. -S. Yang, and G. W. Wu, "Study of a non-isolated bidirectional DC–DC converter," *IET Power Electron.*, vol. 6, no. 1, pp. 30–37, Jan. 2013, doi: 10.1049/iet-pel.2012.0338.

[14] K. Kamalapathi, P. Srinivasa Rao Nayak, and V. K. Tyagi, "Design and implementation of dual-source (WPT + PV) charger for EV battery charging," *Int. Trans. Electr. Energy Syst.*, vol. 31, no. 11, Nov. 2021, doi: 10.1002/2050-7038.13084.

[15] H. Zhang, "Research Advances in Multiport DC Converter of Distributed Generation Systems," *Sci. Technol. Eng. Chem. Environ. Prot.*, vol. 1, no. 10, Dec. 2024, doi: 10.61173/vyvvj411.

[16] C.-M. Lai, M.-H. Pan, and Z.-M. Chen, "A Multi-Port Power Converter with High Voltage Gain," in *2024 6th International Conference on Electrical, Control and Instrumentation*

Engineering (ICECIE), Nov. 2024, pp. 1–6. doi: 10.1109/ICECIE63774.2024.10815695.

[17] H. Tao, A. Kotsopoulos, J. L. Duarte, and M. A. M. Hendrix, "Family of multiport bidirectional DC–DC converters," *IEE Proc. - Electr. Power Appl.*, vol. 153, no. 3, p. 451, 2006, doi: 10.1049/ip-epa:20050362.

[18] H. Tao, J. L. Duarte, and M. A. M. Hendrix, "Multiport converters for hybrid power sources," *PESC Rec. - IEEE Annu. Power Electron. Spec. Conf.*, pp. 3412–3418, 2008, doi: 10.1109/PESC.2008.4592483.

[19] B. Wang, L. Xian, V. R. K. Kanamarlapudi, K. J. Tseng, A. Ukil, and H. B. Gooi, "A Digital Method of Power-Sharing and Cross-Regulation Suppression for Single-Inductor Multiple-Input Multiple-Output DC–DC Converter," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 2836–2847, 2017, doi: 10.1109/tie.2016.2631438.

[20] T. Chaudhury and D. Kastha, "A High Gain Multiport DC-DC Converter for Integrating Energy Storage Devices to DC Microgrid," *IEEE Trans. Power Electron.*, vol. 35, no. 10, pp. 10501–10514, 2020, doi: 10.1109/TPEL.2020.2977909.

[21] A. Mahmoud, M. Ahmed, and A. Hafez, "Multi-Port Converters for Interfacing Renewable Energy Sources:," *Sol. Energy Sustain. Dev. J.*, vol. 13, no. 2, pp. 230–253, Sep. 2024, doi: 10.51646/jsesd.v13i2.246.

[22] S. Kurm and V. Agarwal, "Novel Dual Active Bridge Based Multi Port Converter for Interfacing Hybrid Energy Storage Systems in Electric Vehicles," *2019 IEEE Transp. Electrif. Conf. ITEC-India 2019*, no. d, 2019, doi: 10.1109/ITEC-India48457.2019.ITECIndia2019-223.

[23] M. M. Savrun and A. Atay, "Multiport bidirectional DC-DC converter for PV powered electric vehicle equipped with battery and supercapacitor," *IET Power Electron.*, vol. 13, no. 17, pp. 3931–3939, 2020, doi: 10.1049/iet-pel.2020.0759.

[24] H. Moradisizkoohi, N. Elsayad, and O. A. Mohammed, "An Integrated Interleaved Ultrahigh Step-Up DC-DC Converter Using Dual Cross-Coupled Inductors with Built-In Input Current Balancing for Electric Vehicles," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 8, no. 1, pp. 644–657, 2020, doi: 10.1109/JESTPE.2019.2943301.

[25] P. Ramesh, P. Kumar Gouda, A. Rameshbabu, G. Ramanathan, and C. Bharatiraja, "An isolated multi-port bidirectional DC-DC converter for EV applications," *Mater. Today Proc.*, vol. 68, pp. 1853–1859, 2022, doi: 10.1016/j.matpr.2022.08.047.

[26] A. E B, B. Mathew Jos, K. Boby, and M. Gibi, "Multiple output high gain DC-DC converter," *Mater. Today Proc.*, vol. 58, pp. 540–546, 2022, doi: 10.1016/j.matpr.2022.03.060.

[27] M. M. Savrun, M. İnci, and M. Büyük, "Design and analysis of a high energy efficient multi-port dc-dc converter interface for fuel cell/battery electric vehicle-to-home (V2H) system," *J. Energy Storage*, vol. 45, no. November 2021, 2022, doi: 10.1016/j.est.2021.103755.

[28] S. Surya and M. N. Arjun, "Mathematical Modeling of Power Electronic Converters," *SN Comput. Sci.*, vol. 2, no. 4, p. 267, Jul. 2021, doi: 10.1007/s42979-021-00637-1.